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Efficiency of a bioaugmentation treatment for faecal sludge and agronomic valorisation of the resulting compost: a case study from the Ngoa-Ekélé neighbourhood, Yaoundé (Cameroon)

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Highlights

- Bioaugmentation with a *Bacillus* consortium lowered total nitrogen from 110 to 2.72 mg/L (97.5%).
- Total phosphorus fell from 131.2 to 4.89 mg/L (96.3%) after 14 days of treatment.
- Faecal indicator bacteria fell by 95.9% (E. coli) to 99.5% (faecal streptococci).
- Sludge height and mass declined together during treatment (r = 0.92).
- Compost-amended maize grew taller than unamended controls (62.2 cm vs. about 25 cm).

Abstract

In low-income cities, most households rely on onsite sanitation, and the faecal sludge it produces is rarely treated. This study evaluated a bioaugmentation treatment using a commercial *Bacillus*-based microbial consortium on faecal sludge from septic tanks in the Ngoa-Ekélé neighbourhood of Yaoundé, Cameroon, and assessed the agronomic value of the resulting compost. A household survey (n = 200) first described local sanitation practices. Two sludge samples (4 kg and 3 kg) were then seeded with the consortium, reseeded on day 8 and monitored for 14 days for mass, height, colour, odour and appearance; physicochemical and microbiological parameters were measured before and after treatment. Total nitrogen fell from 110 to 2.72 mg/L (97.5%) and total phosphorus from 131.2 to 4.89 mg/L (96.3%), while potassium rose from 4.8 to 12 mg/L. *Escherichia coli* and faecal coliforms decreased by 95.9% and faecal streptococci by 99.5%; faecal streptococci met the discharge limit, but faecal coliforms did not. Height and mass declined in parallel (Pearson r = 0.92), and the sample that received twice as much consortium per kilogram of sludge lost more of both. Maize seed germination reached about 90% on the soil–compost mix and 100% on pure compost, against about 70% on unamended soil, and after one month compost-amended maize reached 62.2 cm against about 25 cm for the unamended control. Low-cost Bacillus-based bioaugmentation can turn faecal sludge into a usable soil amendment. The trial used only two samples, with no uninoculated control and a single before/after analysis, and faecal coliforms stayed above the limit. Longer, replicated trials are needed before field use, and until then the compost should be used with restrictions.

Keywords: *Faecal sludge; bioaugmentation; Bacillus; onsite sanitation; pathogen reduction; compost; phytotoxicity.*

1. Introduction

Faecal sludge management is a problem that few cities in low- and middle-income countries have solved. Where awareness of the risks remains limited, informal and poorly secured practices persist [1]. In sub-Saharan Africa, urban growth is outpacing the capacity of local authorities to build sanitation infrastructure, so emptying services remain limited and costly and illegal dumping is common [2, 3]. Cameroon follows the same pattern. Quantification work in Yaoundé [4] and characterisation work in Bangangté, West Region [5], both show that onsite sanitation dominates and that no structured treatment chain has yet taken hold; a review of faecal sludge sanitising methods reaches similar conclusions for low-income settings in general [6]. Without treatment, faecal sludge is often discharged directly into the environment, and soils and groundwater in peri-urban African areas carry persistent faecal pollution [7], with direct consequences for health [8].

Where centralised sewerage is lacking, faecal sludge management has to work on small budgets and over the long term [9]. Two obstacles regularly stand in the way: emptying services are hard to reach, and those that exist are often too expensive for households. Dar es Salaam illustrates both. Informal emptying there exposes operators and residents to direct health risks [10], and rising rainfall variability disrupts emptying, transport and treatment in the city's low-lying informal neighbourhoods [11]. The available treatment routes (physical, chemical and biological, the last including composting, anaerobic digestion and bioaugmentation) differ widely in cost and performance depending on local conditions [12, 13]. Bioaugmentation consists of adding a selected microbial consortium to speed up the degradation of organic matter and the reduction of pathogens [14, 15]. It needs no heavy infrastructure, and a recent systematic review of faecal sludge treatment in sub-Saharan Africa lists it among the options compatible with several Sustainable Development Goals [13].

The evidence on bioaugmentation is mixed, however. Inocula have improved organic-load reduction and compost maturity in several recent trials, for example in the short-term stabilisation of sewage sludge loaded with pharmaceutical residues [16] and in food-waste composting with a consortium of *Bacillus subtilis*, *B. amyloliquefaciens* and *Pseudomonas aeruginosa* [17]. In contrast, laboratory and field tests of commercial pit-latrine additives found little or no measurable effect on sludge accumulation [18, 19]. Most positive results also come from industrial settings or engineered plants; trials in a system simple enough for a household or a small sanitation unit in sub-Saharan Africa are rarely reported. In Cameroon, a recent critical review of constructed wetlands for wastewater and faecal sludge treatment notes that applied research on biological treatment remains fragmented, for lack of standardised design criteria and long-term monitoring data [20], although planted drying beds for faecal sludge have been tested in the country for more than a decade [21].

The present study takes up this question with a case from the Ngoa-Ekélé neighbourhood of Yaoundé. It evaluates a bioaugmentation treatment applied to septic-tank sludge and characterises the agronomic value of the resulting compost. The work had three objectives: (i) to establish a baseline of onsite sanitation and faecal sludge management practices in the study area; (ii) to characterise the sludge physicochemically and microbiologically before and after microbial seeding; and (iii) to assess the agronomic quality of the resulting compost, first with a phytotoxicity test and then with a maize growth trial. There is also an economic interest: turning a discarded material into a soil amendment could lower emptying costs and support local operators, as resource-recovery studies have argued for faecal sludge elsewhere [22]. The treatment itself was followed day by day for 14 days.

2. Materials and methods

The methods follow the order of the work. The baseline survey (section 2.4) describes the socio-sanitary context in which the sludge is produced and managed. Sampling and initial characterisation (sections 2.5 and 2.6) give a physicochemical and microbiological baseline for each of the two treated samples. Both samples then went through the same bioaugmentation protocol (sections 2.7 and 2.8) but with different consortium doses, so the kinetic differences reported in section 3 are discussed in relation to dosing. The compost assessment (section 2.9) checks whether the removal measured in the laboratory gives a product that can be used in agriculture.

2.1. Regulatory framework and quality references

Physicochemical and microbiological analyses followed Rodier et al. [23] and the methods compiled for faecal sludge by Velkushanova et al. [24]. Results were compared with the Cameroonian effluent discharge

standard NC 2867:2021. This standard applies to liquid effluents, not to sludge, so it is used here only as an indicative benchmark; agronomic safety was judged against the WHO guidelines for the use of excreta in agriculture [25]. The microbial consortium complies with AFNOR X42-040 (class 1), which covers the safety of biological wastewater treatment products for humans and the environment. The functional analysis of the treatment device drew on AFNOR NF X50-151 (needs analysis), which defines the expected product, here a treated sludge fit for reuse, through three questions: what the treatment is for, what technical function it performs, and how it performs it. On this basis, the objective of the biological treatment was set as stabilising the organic matter and reducing pathogens to levels compatible with a regulated agronomic use.

2.2. Study site and rationale

The study was carried out in the Ngoa-Ekélé neighbourhood, Yaoundé III district (Centre Region, Cameroon; approximately 3°51′ N, 11°30′ E), which borders the Olézoa, Mvolyé and Melen neighbourhoods. In its low-lying, marshy parts there are no protected drinking-water points, some toilets discharge straight into waterways, waste is dumped into the drains and basic hygiene rules are widely ignored. The site was chosen because its population spans every socio-economic category, because no previous survey had covered this precise area, and because residents remain exposed to faecal-related disease. The biological treatment itself was carried out at the Camp-SIC Cité-Verte wastewater treatment plant in Yaoundé, where sludge from the plant has already been used in a vermicomposting trial [26].

2.3. Materials

Field equipment included the bio-latrine product (Biolatrine®, a microbial consortium marketed by Exochems Biotech, France), 10 L buckets and jerrycans for treating and storing samples, a wooden rod for homogenising sludge in the pit, a GPS unit (Garmin Ltd., Olathe, Kansas, USA), personal protective equipment (boots, gloves, face masks, gas mask, helmet, goggles), a sampling syringe, maize seeds, sample labels, a graduated ruler and a portable pH meter. Laboratory equipment comprised a grinder, an analytical balance, a DR/3900 spectrophotometer (Hach Company, Loveland, Colorado, USA) used with Hach reagents, Palintest reagents and photometer (Palintest Ltd., Gateshead, UK), an oven (105 °C) for dry matter, a muffle furnace (550 °C) for volatile solids, Petri dishes, filter membranes, incubators and a colony counter for microbiological analysis, and standard glassware.

The equipment was chosen for a heterogeneous substrate and a laboratory with limited resources. With ready-to-use reagents, the spectrophotometer gives nutrient concentrations without lengthy calibration. Oven drying followed by calcination gives the dry matter and the organic (volatile) fraction, which complement the nitrogen, phosphorus and potassium assays. Such equipment is standard in water and sludge quality control laboratories and was judged sufficient for the comparisons made here; more advanced instrumentation (chromatography, mass spectrometry, molecular methods) was not available, a limitation discussed in the conclusion.

2.4. Baseline assessment, survey and observation

Two instruments were used. A structured questionnaire was first administered to households, covering their sanitation facilities, emptying practices, awareness of faecal sludge management and the measures they take against waterborne disease and odour nuisance. Field observation then confirmed or qualified their answers. In the absence of a complete list of households in the neighbourhood, the 200 households were selected purposively, to cover the range of socio-economic categories and housing types found in Ngoa-Ekélé, rather than at random from a sample size calculated in advance. This approach captures the diversity of local practices but does not make the sample statistically representative of the whole neighbourhood. The survey was carried out with the oral authorisation of the academic supervisor. All respondents were adults; of the 216 heads of household or adult members approached, 200 (92.6%) agreed to take part voluntarily and answered the questionnaire.

2.5. Faecal sludge sampling

Two faecal sludge samples were collected from septic tanks in Ngoa-Ekélé, 4 kg for sample 1 and 3 kg for sample 2. Sampling used a suitable syringe after the sludge had been homogenised in the pit with a wooden rod, and the samples were then kept in 10 L jerrycans until they reached the laboratory.

2.6. Physicochemical and microbiological analysis before/after treatment

The analyses covered pH, total phosphorus, total nitrogen, potassium, ammonia, organic carbon, nitrate, dry matter, volatile solids, iron and faecal indicator bacteria (*E. coli*, faecal coliforms, faecal streptococci). All determinations were made on aliquots (10–40 mL depending on the parameter) of the homogenised raw sludge, without prior extraction or phase separation. pH was measured electrochemically after probe stabilisation (EN 15933). Dry matter was determined by oven drying at 105 °C for 2 h; reference methods for sludge prescribe drying to constant mass (Standard Methods 2540 G; EN 15934), so the shorter drying time may slightly underestimate the water content. Volatile solids were obtained by calcining the dried residue at 550 °C for 1 h (Standard Methods 2540 G; EN 15935), using equations (1) and (2), where M0 is the mass of the empty crucible, M1 the mass of the crucible with the fresh sample, M2 the mass after drying and M3 the mass after calcination [24]. Nitrate (zinc reduction and diazotisation, Palintest Nitratest, photometer program 63) and potassium (sodium tetraphenylborate turbidimetry, Palintest, program 30) were measured with Palintest reagents. Organic carbon was determined by wet oxidation (Walkley–Black method, ISO 14235): potassium dichromate in sulfuric medium, back-titration of the excess dichromate with Mohr's salt. Total nitrogen was determined by Kjeldahl mineralisation with concentrated sulfuric acid and a copper/potassium sulfate catalyst, followed by distillation of ammoniacal nitrogen (EN 13342), and total phosphorus by persulfate digestion followed by the molybdate–ascorbic acid method (Hach method 8190, equivalent to ISO 6878) [23]. Ammonia was determined with the Nessler method (Hach method 8038) and iron with the 1,10-phenanthroline method (Hach FerroVer, method 8008) on the DR/3900 spectrophotometer. Bacteria were enumerated after serial decimal dilutions in sterile physiological water by membrane filtration (0.45 µm), with the selective media and incubation conditions of the reference methods: *E. coli* on chromogenic coliform agar at 36 °C for 21–24 h (ISO 9308-1), faecal coliforms on m-FC agar at 44.5 °C for 24 h (Standard Methods 9222 D) and faecal streptococci on Slanetz-Bartley agar at 36 °C for 44 h (ISO 7899-2); results are expressed in CFU/100 mL.

$$\%DM = [(M2 - M0) / (M1 - M0)] \times 100 \quad (1)$$

$$\%VS = [(M2 - M3) / (M2 - M0)] \times 100 \quad (2)$$

2.7. Selection and preparation of the microbial consortium

The bioaugmentation product (Biolatrine) is a patented consortium containing strains of several bacterial species, including *Bacillus pumilus*, *Bacillus megaterium* and *Paenibacillus polymyxa*, selected for their ability to degrade organic matter (fats, cellulose, excreta). It complies with AFNOR X42-040 (class 1); the manufacturer states that it is neither pathogenic nor toxic and claims deodorising, disinfecting and anti-clogging properties. To activate the strains, one 50 g sachet was dispersed in a known volume of water (1.5 L for sample 1,1 L for sample 2) and stirred briefly to release the microorganisms from their granular carrier.

2.8. Seeding, reseeding and treatment monitoring

Sludge pH was measured first (target range 6 to 9, favourable to bacterial growth), and the activated solution was then added (seeding, day 1). Sludge height in its container was recorded with a graduated ruler before treatment as the baseline. On day 8, the samples were reseeded by adding the consortium directly to the sludge: 50 g for sample 1 and 100 g for sample 2. Over the whole treatment, sample 1 therefore received 100 g of consortium for 4 kg of sludge (25 g/kg) and sample 2 received 150 g for 3 kg (50 g/kg). Odour, colour, appearance and height (cm) were recorded daily for 14 days, and mass (kg) on days 1, 4, 7, 10 and 13. The containers were kept in the dark during the first phase (days 1 to 7) and in the light during the second (days 8 to 14). Because the change to light coincided with reseeding, the design cannot separate the effect of light from that of the second inoculation, and the two phases are compared descriptively only.

2.9. Compost quality assessment

Treated sludge was sampled in the morning into a labelled glass jar, kept at 4 °C and taken to the laboratory in a cooler within 24 hours. One month after the end of treatment, a phytotoxicity test adapted from Zucconi et al. [27] was run with maize seeds sown at shallow depth in plastic pots containing three substrates: P0 (soil only, control), P1 (soil mixed with treated sludge) and P2 (treated sludge only). The germination rate

(GR) and the relative germination (RG) of P1 and P2 were calculated with equations (3) and (4), where Ng is the number of germinated seeds and Ns the number of seeds sown [27, 28].

$$GR\ (\%) = (Ng / Ns) \times 100 \quad (3)$$

$$RG\ (\%) = [GR(substrate) / GR(P0)] \times 100 \quad (4)$$

Root elongation was not measured, so the Zucconi germination index, which combines germination and root length, could not be calculated. The number of seeds sown per pot and the soil-to-sludge ratio of P1 were not recorded. A one-month pot trial then followed maize growth on the same substrates, recording leaf count, leaf colour, plant height and stem diameter.

2.10. Data analysis

Data were analysed quantitatively (physicochemical and microbiological parameters before and after treatment, removal rates) and qualitatively (changes in odour, colour and appearance), the qualitative observations being sorted following a failure mode and effects analysis (FMEA) of the treatment process [29]. Removal rates (R) were calculated with equation (5), where Ci and Cf are the values before and after treatment.

$$R\ (\%) = [(Ci - Cf) / Ci] \times 100 \quad (5)$$

A Pearson correlation between sludge height and mass was computed post hoc on the five dates on which both variables were recorded for both samples (days 1, 4, 7, 10 and 13; n = 10). These ten points are repeated measurements on two samples that started from different values, so the coefficient describes the consistency between the two indicators and is not used as an inferential test.

3. Results and discussion

3.1. Socio-sanitary context and faecal sludge management practices

In the 200 surveyed households, manual-flush toilets (35%) and traditional pit latrines (22.5%) are the most common facilities, followed by mechanical-flush toilets (17.5%) and VIP latrines (12.5%); the type of facility was not recorded for the remaining 25 households (12.5%), and no ECOSAN latrine was recorded. Households rate their own facilities poorly: 82.5% consider them unimproved and 81.5% say they are dissatisfied with them. Mechanical emptying is the most common method (60%, against 40% for manual emptying). Households paid 30,000–40,000 FCFA (49%), 40,000–50,000 FCFA (35%) or more than 50,000 FCFA (16%) per trip, depending on truck capacity, which 67.5% of households find expensive or very expensive. Just over half of the households (51.5%) had heard of biological faecal sludge treatment products, yet none had ever used one, which points to a problem of access rather than rejection. The same combination of dominant onsite sanitation, costly emptying and frequent illegal dumping was described in the twelve cities compared by Peal et al. [3] and, more recently, in Kigali [30]. Section 3.9 returns to this access gap.

3.2. Physicochemical and microbiological characteristics of the sludge

Table 1 gives the physicochemical and microbiological characteristics of the sludge before and after treatment.

Table 1. Sludge characteristics before and after biological treatment

Parameter	Before treatment	After treatment	NC 2867:2021 limit (indicative)
pH	6.68 – 6.89	8.19	6 – 9
Total phosphorus P (mg/L)	131.2	4.89	10
Total nitrogen N (mg/L)	110	2.72	20
Potassium K (mg/L)	4.8	12	50
Ammonia NH_3 (mg/L)	0.08	n.m.	–
Organic carbon C (mg/L)	119.3	n.m.	–
Nitrate NO_3^- (mg/L)	3.12	n.m.	15 – 20
Dry matter DM (%)	93.32	n.m.	–
Volatile solids VS (%)	74.51	n.m.	–
Iron Fe (mg/L)	6.24	n.m.	–
E. coli (CFU/100 mL)	98,400	4,000	–
Faecal coliforms (CFU/100 mL)	123,000	5,100	2,000
Faecal streptococci (CFU/100 mL)	23,500	125	1,000

n.m.: not measured; –: no limit set in NC 2867:2021, which applies to liquid effluents and is used here as an indicative benchmark only. Values are for one composite sample of the raw sludge (before) and one of the treated sludge (after); pH was 6.89 and 6.68 in the two determinations made before treatment.

Before treatment, total phosphorus (131.2 mg/L against a 10 mg/L limit), total nitrogen (110 against 20 mg/L), faecal coliforms (123,000 against 2,000 CFU/100 mL) and faecal streptococci (23,500 against 1,000 CFU/100 mL) are far above the Cameroonian discharge limits, and *E. coli*, for which the standard sets no limit, reaches 98,400 CFU/100 mL. Potassium (4.8 mg/L) and nitrate (3.12 mg/L) are below the reference values, and pH (6.68–6.89) lies within the discharge range. The ammonia value (0.08 mg/L) is unusually low; ammoniacal nitrogen is generally much higher in raw faecal sludge [9]. The low value may reflect ammonia losses during storage and transport and is not interpreted further. The dry matter value (93.32%) is not plausible for a sludge described as liquid, since septic-tank sludge usually contains only a few percent of total solids [31, 32]. The calculation used (M2/M1) probably did not subtract the mass of the container, which inflates the result; the value is reported for completeness but is not interpreted. A high organic and bacteriological load with few available mineral nutrients is what one expects from a sludge that has barely stabilised.

These results agree with recent Cameroonian work. In Bafoussam, raw sludge from septic tanks and pit latrines showed a high organic and bacteriological load and incomplete mineralisation of nitrogen and phosphorus, close to what is observed here, and the authors concluded that treatment is needed before any agricultural use [33]. Faecal sludge characteristics vary widely with containment type, storage time and emptying practice [31], so these values describe the two septic tanks sampled rather than the neighbourhood as a whole. The very low nitrate concentration before treatment indicates that little nitrification had taken place in the untreated sludge, as expected under partial anaerobiosis.

3.3. Kinetics of the biological treatment: height, mass, colour, odour and appearance

Physical monitoring over 14 days shows how fast and how regularly the organic matter degraded under the consortium. Figure 1 shows sludge height.

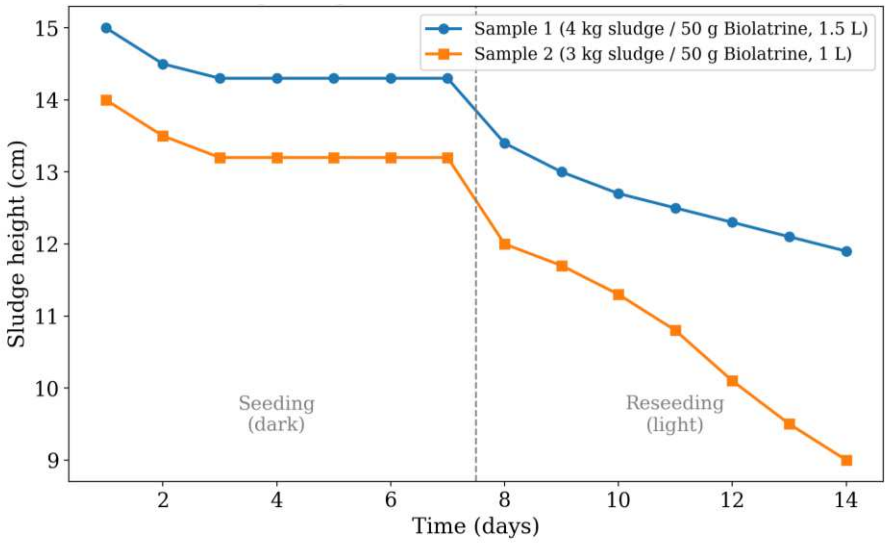


Figure 1. *Sludge height over the course of treatment*

Sludge height fell from 15 to 11.9 cm in sample 1 (-20.7%) and from 14 to 9 cm in sample 2 (-35.7%). The curves show three stages: a rapid drop during the first two days in the dark, a near plateau until day 8, and a renewed decline after reseeding, in the light, from day 8 to day 14. Sample 2 lost more height than sample 1. It also received more consortium per kilogram of sludge (50 g for 3 kg against 50 g for 4 kg at seeding, then 100 g against 50 g at reseeding, 50 against 25 g/kg overall) and was activated in a smaller volume of water (1 L against 1.5 L).

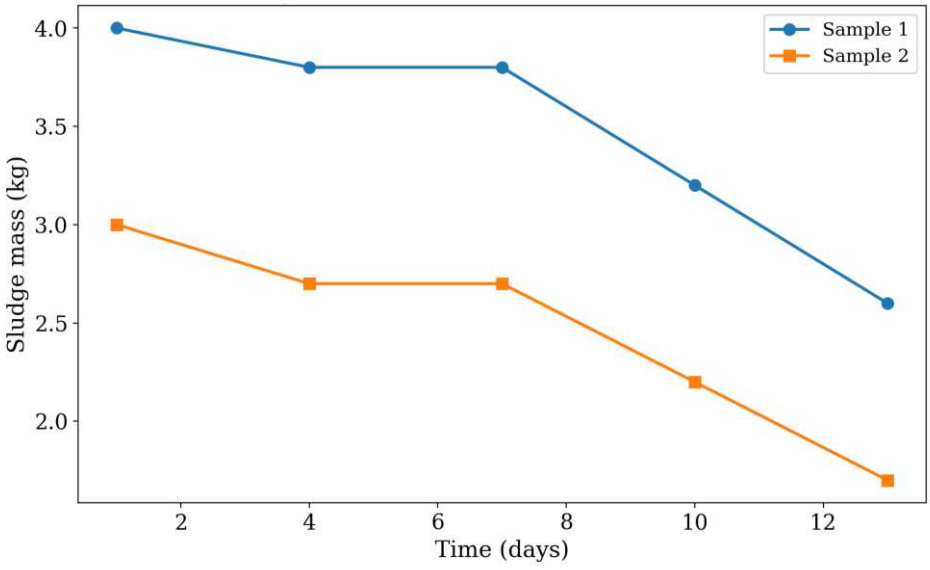


Figure 2. *Sludge mass over the course of treatment*

Mass followed the same course (Figure 2), from 4 to 2.6 kg in sample 1 (-35%) and from 3 to 1.7 kg in sample 2 (-43.3%), with the same three stages. Odour, strong on day 1, was barely perceptible by day 3. Colour changed from the initial dark tone to brown and then to dark green around day 10, and the sludge thickened, first to a paste and then to a dense mass by the end of treatment.

Three processes can account for this physical reduction: microbial degradation of organic matter, which reduces the solid fraction and the volume of sludge; the release of gases (CO_2 and, in anaerobic zones, CH_4); and the loss of interstitial water through evaporation and metabolic activity. The renewed decline after reseeding is consistent with work on repeated inoculation. In pilot-scale sewage sludge composting, regular multi-step inoculation with a genetically characterised *Bacillus subtilis* strain extended the thermophilic

phase and accelerated maturation compared with a single late inoculation [34], and multi-stage inoculation has been used to steer bacterial and fungal succession during municipal solid waste composting [35]. A meta-analysis of composting trials has also quantified the effect of microbial inoculation on nutrient turnover and lignocellulose degradation [36]. In our trial, however, the effect of reseeding cannot be separated from the change from dark to light (section 2.8).

The larger reduction in sample 2 is most simply explained by its higher dose: twice as much consortium per kilogram of sludge as sample 1. The smaller activation volume may have added to this by delivering a more concentrated inoculum, but the two factors vary together and, with one sample per condition, their effects cannot be separated. Commercial additives do not always work. Laboratory and field trials in South African VIP latrines found no significant effect of several products on sludge accumulation [18], and tests in simulated pits found little or no gain in solids degradation [19]. The dose effect seen here still needs confirmation in replicated trials that include an uninoculated control (section 4).

Height and mass were strongly correlated ($r = 0.92$, $r^2 = 0.85$; $n = 10$, days 1, 4, 7, 10 and 13 in both samples). The two variables were measured independently, one with a ruler and the other with a balance, so their agreement suggests that the loss of volume and the loss of mass come from the same degradation process. The coefficient should not be over-read: the points are repeated measurements on two samples that started from different values, and pooling them can inflate the correlation.

3.4. Effect of treatment on nutrient parameters (nitrogen, phosphorus, potassium)

This step measured the effect of treatment on the major nutrients, which determine the value of the product as an organic amendment. Figure 3 shows nitrogen, phosphorus and potassium before and after treatment.

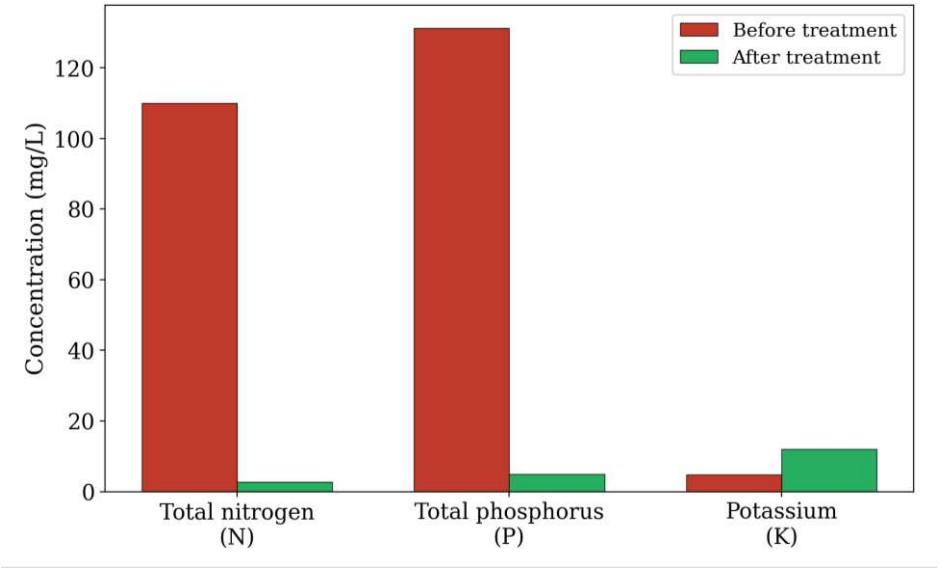


Figure 3. *Nitrogen, phosphorus and potassium levels before and after treatment*

Total nitrogen fell from 110 to 2.72 mg/L (-97.5%), below the 20 mg/L discharge limit, and total phosphorus from 131.2 to 4.89 mg/L (-96.3%), below the 10 mg/L limit. Potassium rose from 4.8 to 12 mg/L (+150%) and stayed below 50 mg/L. pH rose from 6.68–6.89 to 8.19, within the 6–9 range set for the treatment (section 2.8).

These decreases do not mean that nitrogen and phosphorus were destroyed; they left the analysed fraction (section 2.6). Nitrogen can leave the system. Organic nitrogen is ammonified, part of the ammonium is lost as ammonia, especially once pH rises above 8 as it did here, and nitrate formed in aerobic zones can be denitrified [37, 38]. Phosphorus, in contrast, has no significant gaseous form and cannot escape from a closed container. A 96% drop in measured phosphorus must then reflect its transfer to forms that were not measured: uptake into microbial biomass, adsorption onto particles, and precipitation as poorly soluble salts, which becomes more likely as pH increases [37]. In sludge and faecal-sludge composting, most of the phosphorus stays in the solid compost [39, 40]. The low phosphorus concentration after treatment means that little phosphorus remained in soluble form, not that the compost lost it; this would need to be confirmed by measuring total phosphorus in the solid product.

The rise in potassium has two likely causes. Potassium is not volatile and remains in the system, so the 35–43% loss of mass (section 3.3) concentrates it; this alone would raise its concentration by a factor of about 1.5 to 1.8. In addition, degradation of the organic matrix releases potassium held in cells and organic debris into solution as K^+. Both effects are usual in composting, where potassium accumulates in the final product instead of being lost [37]. For the compost this is favourable, because potassium is a major nutrient for maize; in forest soils amended with green-waste compost, the humic fraction of the compost has also been linked to higher available nitrogen, phosphorus and potassium [41].
The loss of soluble nitrogen and phosphorus and the release of potassium fit a progressive mineralisation of the organic matter, which is also what the changes in appearance and colour suggested (section 3.3).

3.5. Effect of treatment on microbiological load

The second aim was sanitary: to measure how much the treatment reduced faecal indicators, a precondition for any agricultural use of the compost. Figure 4 shows the results.

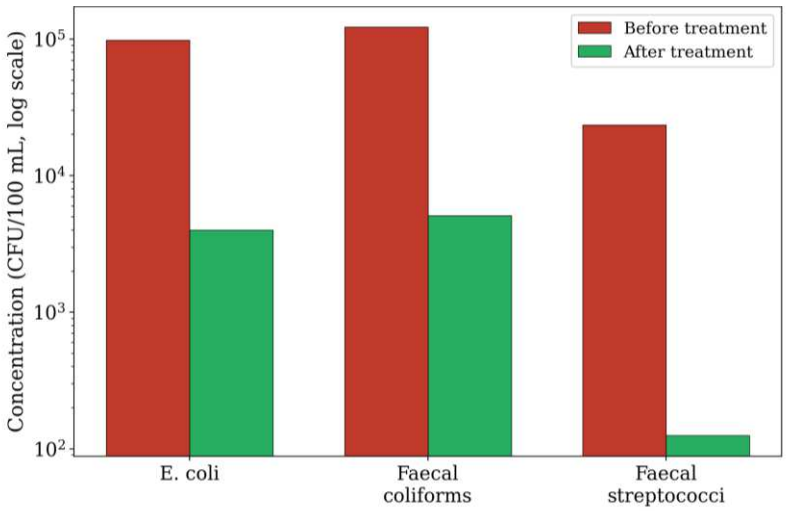


Figure 4. *Microbiological reduction before and after treatment*

All three indicators fell sharply: *E. coli* from 98,400 to 4,000 CFU/100 mL (-95.9%), faecal coliforms from 123,000 to 5,100 CFU/100 mL (-95.9%) and faecal streptococci from 23,500 to 125 CFU/100 mL (-99.5%). Faecal streptococci fall below the 1,000 CFU/100 mL limit, but faecal coliforms remain above the 2,000 CFU/100 mL limit. Fourteen days were not enough to bring every indicator within the discharge standard.

A reduction of more than 95% that still leaves an indicator above its limit is not unusual. In rural South Africa, faecal indicators and enteric pathogens have been traced from onsite sanitation facilities into groundwater [42], and studies on faeces and faecal sludge show that pathogen die-off depends on temperature, pH, moisture and time [43–45]. Inoculation can help: in swine-manure composting, a compound inoculant of three *Bacillus* strains and one yeast raised peak temperature and the *Bacillus* population, which contributed to pathogen removal [46]. Our treatment, however, ran at ambient temperature for 14 days, without the thermophilic phase that sanitises compost heaps. In that case the WHO guidelines apply: treated excreta that do not meet microbial targets can be used only with additional barriers, such as further storage, restriction to crops not eaten raw and protection of workers [25]. The treated sludge can already be used as an amendment (section 3.6), but not yet for unrestricted use.

3.6. Phytotoxicity test and germination index

The phytotoxicity test checked that the compost does not contain phytotoxic compounds (ammonia, organic acids, salts or trace metals) at concentrations that inhibit germination.
Table 2 gives the germination results. About 70% of the seeds germinated on unamended soil (P0), about 90% on the soil–compost mix (P1) and 100% on pure compost (P2), so relative germination on the amended substrates was about 130% (P1) and 140% (P2) of the control. One month after the end of treatment, the compost did not inhibit maize germination. It improved it.

Table 2. Germination of maize seeds on the three substrates

Substrate	Germination rate (%)	Relative germination (%)	Root length
P0 (soil, control)	≈ 70	100	n.m.
P1 (soil + treated sludge)	≈ 90	≈ 130	n.m.
P2 (treated sludge)	100	≈ 140	n.m.

Values read from the original germination bar chart; seed counts were not reported. Relative germination calculated with equation (4). n.m.: not measured.

A germination index above 80% is commonly taken to indicate a mature compost free of phytotoxicity [28, 37]. Our test recorded germination only, without root elongation, so it is less sensitive than the full index; relative germination above 100% nevertheless points the same way. The test devised by Zucconi et al. remains the standard biological indicator because it responds to effects on both germination and root elongation [27]; more recent work has refined the extraction conditions and thresholds of the method [47]. During composting of sewage sludge from several Moroccan treatment plants, phytotoxicity likewise decreased as the process advanced [48]. A cattle-manure composting study that modelled germination against maturity [49] and an evaluation of local organic fertilisers in the Ethiopian Rift Valley, where the germination index was the main maturity indicator [50], reached similar conclusions. The test was run one month after the end of treatment, so part of the maturation happened in between.

3.7. Effect of compost on maize growth

This trial tested whether the compost could support maize growth over one month, which measures its agronomic value more directly than germination alone. Figure 5 shows the results.

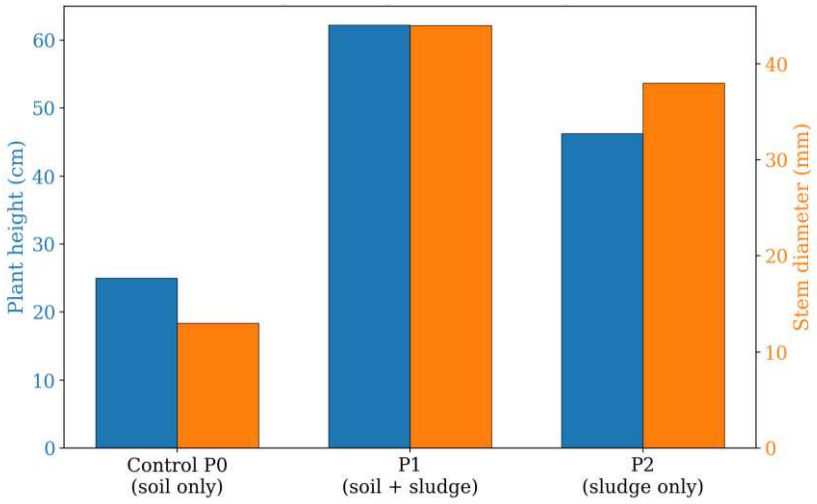


Figure 5. *Maize growth by substrate*

At the end of the trial, plants on P1 (soil and compost) performed best on every parameter: five leaves on average (four on P2, three on the P0 control), a height of 62.2 cm (46.3 cm on P2, about 25 cm on P0) and a stem diameter of 4.4 cm (3.8 cm on P2, 1.3 cm on P0; Figure 5). These values, recorded as stem diameters in the original data, are high for one-month-old maize and may correspond to stem circumference; they are reported as recorded. Plants on P1 and P2 stayed dark green throughout, whereas the control turned from dark green to light green and then yellow.

Better growth on amended substrates than on unamended soil agrees with trials of organic and potassium-rich amendments on maize [51] and with two recent studies in West Africa. In the Guinea savannah of northern Ghana, compost applied alone or with biochar and mineral fertiliser increased maize growth and yield over two cropping seasons, with yield gains above 100% for the best combinations [52]. On tropical Alfisols in Zaria, Nigeria, compost improved the release of nitrogen, phosphorus and potassium over time, soil quality and maize yield compared with the control [53]. Faecal sludge has also been turned into compost and co-compost for farmers in Ghana [54, 55]. The yellowing of the control is a typical sign of nitrogen deficiency. That the amended plants did not yellow, although soluble nitrogen had dropped in the analysed

fraction (section 3.4), suggests that the compost supplied nitrogen in organic forms that mineralised gradually in the soil, together with potassium and organic matter. Nutrients were not measured in the solid compost, so this explanation remains to be checked.

3.8. Economic considerations

No full cost accounting was made. This section only compares the order of magnitude of the tested treatment with current practice as reported in the survey (section 3.1), for a household or a small community structure.

Sample 1 received 100 g of consortium (50 g at seeding and 50 g at reseeding) for 4 kg of sludge, and sample 2 received 150 g (50 g, then 100 g) for 3 kg. The two figures are not directly comparable, because biological treatment does not replace emptying. Its purpose is to space emptying out, by reducing the volume of sludge that accumulates in the pit, and to yield a compost instead of a waste to be disposed of. The 20.7–43.3% reduction in height and mass (section 3.3) gives an indirect idea of the storage capacity that could be gained between two emptying cycles.

The manufacturer presents longer intervals between emptying as the main economic benefit for households. Field evidence on pit additives is more cautious [18, 19], and the gain in storage capacity would have to be measured in real pits. Cost is often what holds adoption back. In rural Kenya, willingness to pay limited the uptake of improved sanitation [56], and in an informal settlement in Nairobi, households were willing to pay less than the cost of a safer manual emptying service [57]. Selling the compost could offset part of the cost. In Kampala, farmers were willing to pay a premium for certified faecal-sludge compost, although they valued pelletised compost below its production cost [58], and in Haiti and Kenya unclear regulations and undeveloped organic-fertiliser markets are the main obstacles to selling excreta-derived fertilisers [59]. A study of ex situ organic fertiliser production in eleven African countries, Cameroon included, describes a sector still at a formative stage, carried by small initiatives (among them Cameroonian community groups organised as savings circles around compost production) and held back by limited financing and weak market recognition [60]. Biological faecal sludge treatment in Yaoundé is likely to meet the same barriers.

This assessment is indicative and does not replace a cost–benefit analysis. It leaves out the labour of daily monitoring, the investment needed for neighbourhood-scale treatment (tanks, operator protection, compost transport) and the market value of the compost, for which no local market existed in the study area at the time of the work.

3.9. Operational implications and scale-up prospects

The treatment reduced organic, nutrient and bacteriological load together (sections 3.3 to 3.5) and produced an amendment with agronomic value (sections 3.6 and 3.7). The fact that half of the surveyed households knew of such products but none used them (section 3.1) is more likely due to access, information and the lack of local demonstration than to the principle of the treatment, much as formal emptying services are lacking in Dar es Salaam [10]. Demonstrations in the neighbourhood and a local supply of the product would answer both points.

The protocol is simple: activation is quick, monitoring is visual and no heavy equipment is needed. It could be transposed to a household, a group of households or a shared bio-latrine, which fits the resources available in the study area [12]. Two cautions apply. Commercial additives have given inconsistent results in field trials [18, 19], so local demonstrations should include an untreated control. And since faecal coliforms remain above the discharge limit after 14 days (section 3.5), the compost should not yet be applied without restriction. A longer treatment, an additional storage or maturation step and restricted use (mixed with soil rather than applied pure, and not on vegetables eaten raw) are preferable until further validation [25].

4. Conclusion

This work evaluated a bioaugmentation treatment applied to faecal sludge collected in Ngoa-Ekélé (Yaoundé) and the agronomic value of the resulting compost. Over 14 days, total nitrogen fell from 110 to 2.72 mg/L (-97.5%) and total phosphorus from 131.2 to 4.89 mg/L (-96.3%) in the analysed fraction, while potassium rose from 4.8 to 12 mg/L through mass loss and release from the degrading organic matter. *E. coli* and faecal coliforms decreased by 95.9% and faecal streptococci by 99.5%. Sludge height and mass declined together ($r = 0.92$), and the sample that received twice as much consortium per kilogram lost more of both. Maize seed germination was about 90% on the soil–compost mix and 100% on pure compost, against about 70% on unamended soil, and one month after the end of treatment it supported maize growth better than unamended soil (62.2 cm against about 25 cm). A low-cost bioaugmentation treatment can turn raw faecal

sludge, far outside several discharge limits, into a soil amendment whose safety for plants is supported by two biological tests. The survey adds a practical point: more than half of the households know that such products exist, yet none uses them.

These results call for caution. The trial rests on two samples treated in parallel with different doses, without an uninoculated control or analytical replicates, so the removal rates describe trends rather than statistically tested differences. The change from dark to light coincided with reseeding. Physicochemical and microbiological parameters were measured only before and after treatment, and nutrients were not measured in the solid compost, so the fate of nitrogen and phosphorus is inferred rather than measured. The germination test did not include root elongation. Trace metals, helminth eggs and the microbial community of the compost were not analysed, and faecal coliforms still exceed the discharge limit after 14 days. The household sample was purposive, so the survey proportions describe the sample rather than the whole neighbourhood.

Further work should include an uninoculated control and replicated batches, vary dose and activation volume independently, extend treatment beyond 14 days, follow nutrients and indicators over time in both the liquid and the solid fractions, and analyse helminth eggs and trace metals before any field use is considered.

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Author contributions (CRediT statement)

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Loundouobe Kapchie Making Love: Investigation, Data curation, Methodology, Writing-original draft;

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics statement

No ethics committee approval was sought for this study. The household survey involved no clinical procedure and no biological sampling of participants, and no personal identifying data were recorded. It was

conducted with the oral authorisation of the academic supervisor. All respondents were adults; they were informed of the purpose of the study and took part voluntarily after giving oral consent. Of the 216 adults approached, 200 agreed to participate.

Data availability

Raw experimental data (survey sheets, treatment monitoring records, physicochemical and microbiological analysis results) originate from fieldwork carried out in Ngoa-Ekélé and at the Camp-SIC Cité-Verte wastewater treatment plant; they can be made available by the corresponding author on reasonable request.

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